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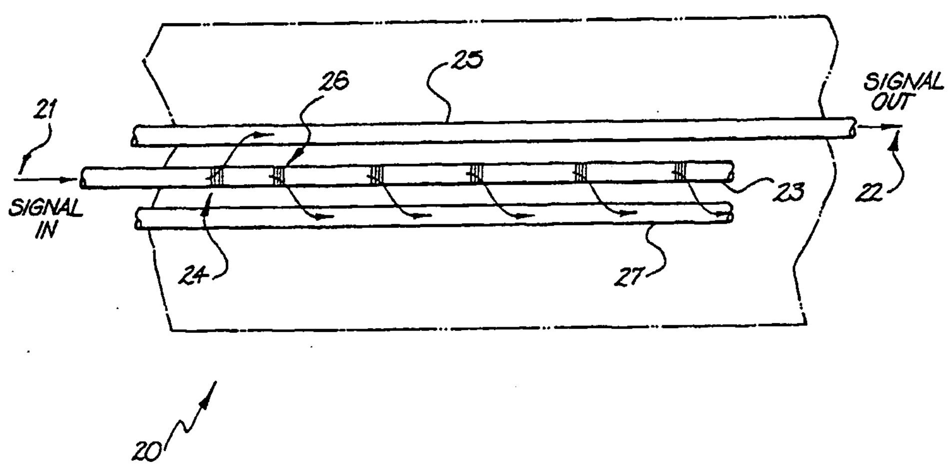
(54) Title: ULTRA-BROADBAND LOW-NOISE GAIN-FLATTENED RARE-EARTH-DOPED FIBRE AMPLIFIER



(57) Abstract

An apparatus for providing flat gain amplification across a broad wavelength range comprising: input means (21) for inputting an input signal to an amplification waveguide means; output means (22) for outputting an output signal comprising an amplified version of the input signal having substantially flat gain characteristics; noise dissipation means (27); amplification waveguide means (24, 26) connected to the input means and the output means, the amplification waveguide means providing for a variable amplification gain of the wavelength components of the input signal, the degree of amplification being proportional to the length of transmission of the input signal along the amplification waveguide means, the amplification waveguide means further comprising a series of output wavelength coupling means (25) positioned along the amplification waveguide means for coupling predetermined amplified wavelengths from the amplification waveguide means to the output means, in addition to noise wavelength coupling means (24, 26) for coupling unwanted amplifications from the amplification waveguide means to the noise dissipation means (27) for dispersion by the noise dissipation means (27).

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Ultra-Broadband Low-Noise Gain-Flattened Rare-Earth-Doped Fibre Amplifier

Field of the Invention

The present invention relates to amplification of optical signals and in particular those signals transmitted through optical fibres and amplified utilising a rare-earth doped fibre amplifier.

Background of the Invention

Recently, the utilisation of optical fibres for communications has become increasingly popular due to their high bandwidth capabilities. The wavelengths normally utilised for optical fibre transmission have been traditionally related to the low attenuation areas of the transmission spectrum of a single mode optical fibre. Turning initially to Fig. 1, there is illustrated the spectrum of a typical attenuation rate for single mode optical fibres. The figure indicates two particular windows of interest for low loss transmission, the first being at approximately 1550nm and the second at 1310nm. The window at 1550nm has become particularly popular for its low attenuation rate.

Recently the all optical rare-earth doped fibre amplifiers have also become increasingly popular for providing for the all optical amplification of an input signal. One particular form of amplifier in popular use is the Erbium doped fibre amplifier (EDFA) which has particularly strong amplification also in the 1550nm region. Fig. 2 illustrates an example of the gain provided by a standard EDFA for different pumping powers (normalised to one with the gain also normalised to one). As can be seen from Fig. 2, the gain profile of an EDFA is highly irregular. In the past, when only a single wavelength is transmitted by an optical fibre, this is not a problem. However, recently wavelength division multiplexed (WDM) systems have been proposed and constructed with, as the name suggests, the optical fibre carrying many different

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channels at different frequencies or wavelengths. Unfortunately, the amplification profile of an EDFA results in each channel experiencing a substantially different gain and hence a WDM system is likely to be problematic for amplification by a EDFA amplifier unless the gain profile can be held to be substantially constant. It will, of course, be noted from Fig. 2 that an EDFA normally provides a degree of useable gain across a broad spectrum of suitable wavelengths however, as can be clearly seen from Fig. 2, the gain spectrum is "swamped" by the central peak.

Summary of the Invention

It is an object of the present invention to provide for an all optical system having a substantially flattened gain spectrum which would be suitable for incorporation in a WDM transmission system.

In accordance with a first aspect of the present invention, there is provided an apparatus for providing flat gain amplification across a broad wavelength range comprising: input means for inputting an input signal to an amplification waveguide means; output means for outputting an output signal comprising an amplified version of the input signal having substantially flat gain characteristics; noise dissipation means; amplification waveguide means connected to the input means and the output means, the amplification waveguide means providing for a variable amplification gain of the wavelength components of the input signal, the degree of amplification being proportional to the length of transmission of the input signal along the amplification waveguide means, series of output wavelength coupling means positioned along the amplification waveguide means or said output means for coupling predetermined amplified wavelengths from the amplification waveguide means to the output means, in addition to noise wavelength coupling means for coupling unwanted amplifications from the amplification waveguide means to the noise dissipation means for dispersion by the

noise dissipation means.

The output wavelength coupling means can comprise a suitably tuned optical grating and the noise wavelength coupling means can also comprise a grating formed along the fibre. The gratings are preferably long period gratings.

The amplification waveguide means can comprise ~~a~~ fibre amplifier such as an Erbium doped fibre amplifier or a Neodymium doped fibre amplifier. The noise waveguide means can comprise the cladding of an optical fibre.

In accordance with a further aspect of the present invention, there is provided a multi-core fibre wherein the cores are structured such that, at predetermined wavelengths, the propagation constants are unmatched but are subsequently matched by the writing of long period gratings.

In accordance with a further aspect of the present invention, there is provided an apparatus for providing flat gain amplification across a broad wavelength range comprising: input means for inputting an input signal to an amplification waveguide means; output means for outputting an output signal comprising an amplified version of the input signal having substantially flat gain characteristics; noise dissipation means; amplification waveguide means connected to the input means and the output means, the amplification waveguide means providing for a variable amplification gain of the wavelength components of the input signal, the degree of amplification being proportional to the length of transmission of the input signal along the amplification waveguide means, a series of output wavelength coupling means positioned along the amplification waveguide means or said output means for coupling predetermined amplified wavelengths from the amplification waveguide means to the output means.

In accordance with a further aspect of the present invention, there is provided a method of for providing flat gain amplification across a broad wavelength range

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comprising: inputting a signal to be amplified to a broad band amplification means having predetermined spatial amplification characteristics; spatially coupling the broad band amplification means to an output means so as to provide for substantially flat gain amplification of the signal to the output means to produce a substantially flat gain amplification output signal; and outputting the substantially flat gain amplified output signal.

Preferably, the method can further provide the step of spatially coupling the broad band amplification means to a noise dumping means so as to provide for the reduction in unwanted amplifications in the broad band amplification means. The spatial coupling can comprise utilising an optical grating to couple the broad band amplification means to the output means.

Brief Description of the Drawings

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 illustrates the typical attenuation rate for single mode fibres;

Fig. 2 illustrates a graph of amplification gain for an erbium doped fibre amplifier (EDFA) for different pumping levels;

Fig. 3 illustrates in schematic form a first illustrative arrangement discussed with reference to the preferred embodiment; and

Fig. 4 illustrates, in schematic form, one form of the preferred embodiment of the present invention.

Description of Preferred and Other Embodiments

In the preferred embodiment an erbium doped fibre amplifier is utilised in conjunction with a grating system to transfer the signal associated with each wavelength from an input channel to an output channel at a position

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determined by the expected gain on the input signal at a particular wavelength. Subsequently, the amplification of noise associated with the input signal of the same wavelength is discarded or "dumped" to a dispersion or noise channel for dissipation. This process is repeated for each signal of interest.

In order to obtain a clear understanding of the preferred embodiment, an initial apparatus is proposed and discussed with reference to Fig. 3. In this design, an input signal 10 is fed to an Erbium doped amplifying core 11 which is placed in close proximity to a second non-amplifying core 12. The two cores 11, 12 exist within a cladding layer 13. Normally, whilst the two waveguides 11, 12 are placed in close proximity however, they are designed such that coupling between them does not occur (eg. by choice of core diameter and refractive index, which whilst providing similar cutoff wavelengths as needed gives differing propagation constants). The waveguide 11 can comprise an EDFA which is doped and pumped strongly. It potentially provides gain across a very large spectrum. However, as noted previously, the strong gain in the peak of the gain spectrum of Fig. 2 swamps the tails. There is a point along the length of the waveguide 11 where any wavelength within the gain band reaches a certain level of gain (say 30dB), those wavelengths at the gain peak experience this overall level of gain at the first part along the length of the amplifier waveguide 11 and those in the tail part of the gain band experience the level of gain in the last part of the waveguide 11. The gain flattening is achieved by coupling the two waveguides 11, 12 together at a certain point eg. 15-17 dependant on the amount of gain experienced at that point for the particular wavelength. The coupling can be provided by means of a grating written into the fibre. Preferably, long period gratings are utilised. The frequency of the grating written will be dependant upon the desired coupling

wavelength. The coupling at point 15 can be for the wavelength receiving maximum gain near the gain peak whereas the coupling at the point 17 can be for the wavelength experiencing a much lower level of gain near the gain tail along the waveguide 11. Hence, the coupling point varies down the length of the fibre according to the wavelength. The position of the gratings eg. 15-17 being adjusted such that the output gain of the output signal 18 is substantially the same for all wavelengths, thereby achieving gain flattening.

Unfortunately, the arrangement of Fig. 3 does not take into account any noise or residual signal that, for example, is not coupled out of the grating 15. Unfortunately, down the subsequent length of the waveguide 11, the residual noise (and signal which was supposed to be coupled out at the point 15) will be amplified dramatically thereby absorbing energy within the waveguide 11 which would otherwise be utilised to amplify other wavelengths. With the very high gains in the channel 11 at the gain peak, spontaneous emissions will potentially experience sufficient amplification to cause lasing. However, the device of Fig. 3 may still be suitable in its own right.

Turning now to Fig. 4, there is illustrated an alternative more suitable arrangement 20. This arrangement is similar to that illustrated in Fig. 3 and includes broadband input signal 21 and amplified output signal 22. An EDFA amplifier is provided 23 and pumped in the usual manner. Taking the example of one wavelength only, a first coupling is provided 24 for coupling the signal to output waveguide 25 as previously described. Along the rest of the fibre a series of gratings eg. 26 are provided for coupling any residual signal and amplified noise from the waveguide 23 to a noise dissipation waveguide 27 with the grating 26 being particularly tuned so as to provide for coupling directly to the noise dissipation waveguide 27. If desired, the noise dissipation waveguide 27 can be the

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cladding of the fibre. The waveguide 27 provides a convenient place to dump the amplified noise before it can accumulate and deplete the gain or cause lasing. In the simple case, as noted previously, the waveguide 27 can comprise the cladding. Alternatively, it could be a doped waveguide which is unpumped as a means for actively removing the noise. A series of gratings 26 can be provided along the waveguide 23 after a first coupling waveguide 24 so as to minimise any amplification of the noise signals remaining after coupling to the output 25.

The arrangement 20 of Fig. 4 illustrates, for clarity, the processing of one wavelength only, with overlapping gratings being written so as to deal with other wavelengths so as to provide for both flat gain coupling to waveguide 25 in addition to noise dumping to waveguide 27. Hence, the preferred embodiment can include a multi-core fibre with coupling provided by overlapping long period gratings. The coupling to the waveguide 25 can occur at each point where the requisite wavelength reaches a certain gain with immediately after the coupling to the output channels 25 all subsequent noise associated with the output frequency being coupled to the "noise dumping" channel 27.

Of course, other arrangements are possible: For example, counter directional pumping might be utilised so as to provide for maximum tail gain; Codirectional and Bidirectional pumping are also possible. Alternatively, a fourth core waveguide could be introduced with appropriate gratings for distribution of the pumping energy in accordance with the needs. In other arrangements gratings can be written in the other waveguides. For example, the gratings could be written to the output and noise waveguides instead of the gain/input waveguides.

In a further alternative arrangement, the noise channel can comprise the cladding. Other arrangements can include, for example, a central output channel around which is circumferentially arranged the gain amplifier and input

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channel and further around which is circumferentially arranged the noise channel. The channels can alternatively be in a different order.

The principles of preferred embodiment can further be extended to other transmission windows. For example, in the 1300nm window Nd^{3+} in silica is known to provide gain in this region but is normally unusable because of strong competitive lasing combined with poor centring on the band of interest. If gain is provided across the whole band, then high efficiency outcoupling of problem parts of the spectrum may result in realistic silica amplifiers for the 1300nm region.

An extension to the preferred embodiment permits efficient pumping of a gain medium from a multimode source. A multimode pump can be launched into a multimode core which runs close to a gain core. The cores are designed such that as far as is possible there is no coupling between either the signal or pump modes of the gain core and any of the modes of the pump core. Gratings are introduced to couple modes of the multimode pump to the fundamental mode of the pump in the gain channel. The spacing of the gratings along the fibre can be such as to allow for strong absorption of those components of the pump already coupled (so that there is negligible back-coupling). In this manner, each mode may be coupled over and absorbed. This has an advantage over existing schemes such as cladding pumping, where the absorption of the pump relies on a simple overlap and the efficiency scales with the areas of the waveguides. This scheme may be particularly advantageous for lasers as well as amplifiers.

Further, it is known that long period gratings are highly sensitive to perturbations. This can be used to effect tuning of the coupling and hence the overall performance. For instance, first order corrections for spectral gain variations due to changes in inversion from changes in signal or pump power could be corrected by, for

instance strain or temperature, tuning of the long period gratings.

It would further be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

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We Claim

1. An apparatus for providing flat gain amplification across a broad wavelength range comprising:

input means for inputting an input signal to an amplification waveguide means;

output means for outputting an output signal comprising an amplified version of said input signal having substantially flat gain characteristics;

noise dissipation means;

amplification waveguide means connected to said input means and said output means, said amplification waveguide means providing for a variable amplification gain of the wavelength components of said input signal, the degree of amplification being proportional to the length of transmission of said input signal along said amplification waveguide means,

a series of output wavelength coupling means positioned along said amplification waveguide means for coupling predetermined amplified wavelengths from said amplification waveguide means to said output means, in addition to noise wavelength coupling means for coupling unwanted amplifications from said amplification waveguide means to said noise dissipation means for dispersion by said noise dissipation means.

2. An apparatus as claimed in claim 1 wherein said output wavelength coupling means comprise an optical grating.

3. An apparatus as claimed in any previous claim wherein said noise wavelength coupling means comprises a grating formed along said fibre.

4. An apparatus claimed in claim 2 or 3 wherein said gratings comprise long period gratings.

5. An apparatus as claimed in any previous claim wherein said amplification waveguide means comprises a fibre amplifier.

6. An apparatus as claimed in claim 5 wherein said fibre amplifier is a rare earth doped fibre amplifier.

7. An apparatus as claimed in claim 6 wherein said fibre amplifier is an Erbium doped fibre amplifier.

8. An apparatus as claimed in claim 1 wherein said noise waveguide means comprises the cladding of an optical fibre.

9. A multi-core fibre wherein the cores are structured such that, at predetermined wavelengths, the propagation constants are unmatched but are subsequently matched by the writing of long period gratings.

10. An apparatus for providing flat gain amplification across a broad wavelength range comprising:

input means for inputting an input signal to an amplification waveguide means;

output means for outputting an output signal comprising an amplified version of said input signal having substantially flat gain characteristics;

noise dissipation means;

amplification waveguide means connected to said input means and said output means, said amplification waveguide means providing for a variable amplification gain of the wavelength components of said input signal, the degree of amplification being proportional to the length of transmission of said input signal along said amplification waveguide means,

a series of output wavelength coupling means positioned along said amplification waveguide means or said output means for coupling predetermined amplified wavelengths from said amplification waveguide means to said output means.

11. A method of for providing flat gain amplification across a broad wavelength range comprising:

inputting a signal to be amplified to a broad band amplification means having predetermined spatial amplification characteristics;

spatially coupling said broad band amplification means to an output means so as to provide for substantially flat gain amplification of said signal to said output means to produce a substantially flat gain amplification output signal; and

outputting said substantially flat gain amplified output signal.

12. A method as claimed in claim 11 further comprising the step of:

spatially coupling said broad band amplification means to a noise dumping means so as to provide for the reduction in unwanted amplifications in said broad band amplification means.

13. A method as claimed in claim 11 or claim 12 wherein said broad band amplification means comprises an optical amplifier.

14. A method as claimed in claim 11 wherein said spatially coupling comprises utilising an optical grating to couple said broad band amplification means to said output means.

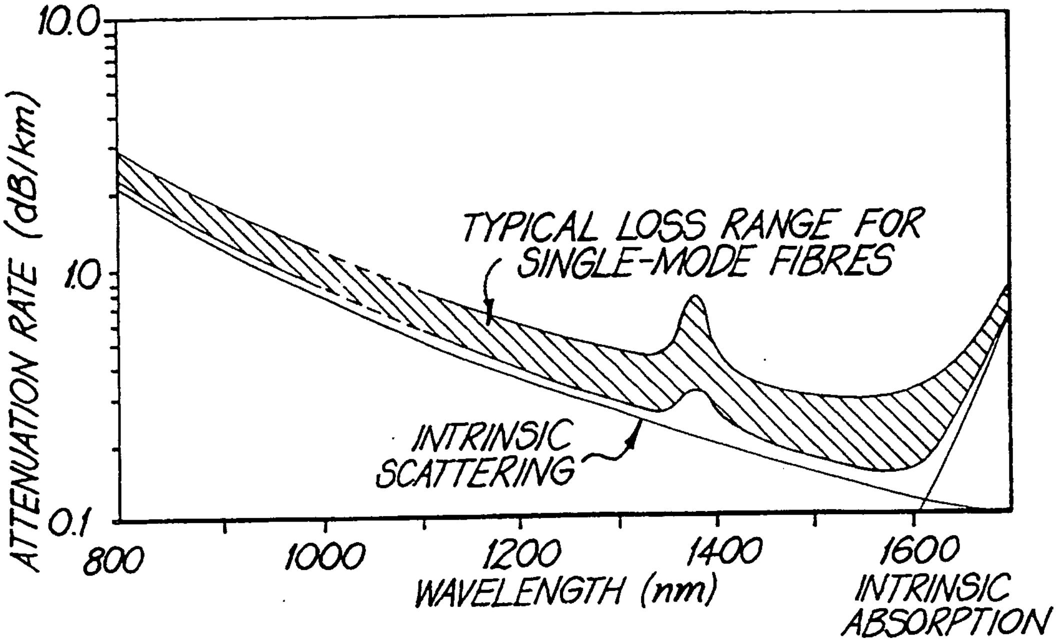
10.0
1.0
0.1
ATTENUATION RATE (dB/km)
TYPICAL LOSS RANGE FOR SINGLE-MODE FIBRES
INTRINSIC SCATTERING
800
1000
1200
1400
1600
WAVELENGTH (nm)
INTRINSIC ABSORPTION

FIG. 1

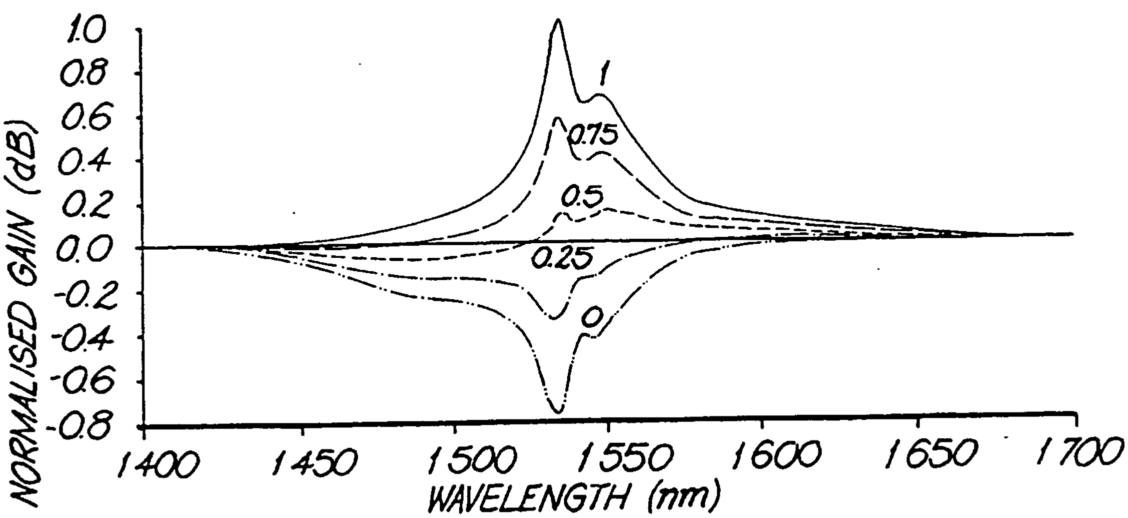
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
NORMALISED GAIN (dB)
1
0.75
0.5
0.25
0
1400
1450
1500
1550
1600
1650
1700
WAVELENGTH (nm)

FIG. 2

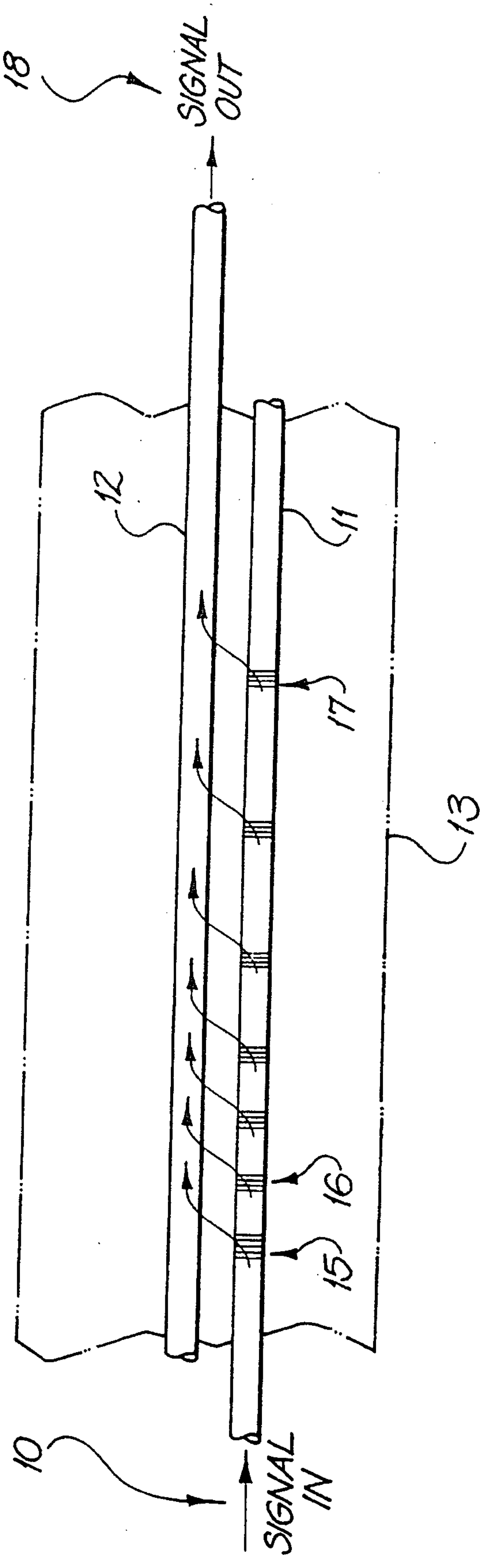

FIG. 3

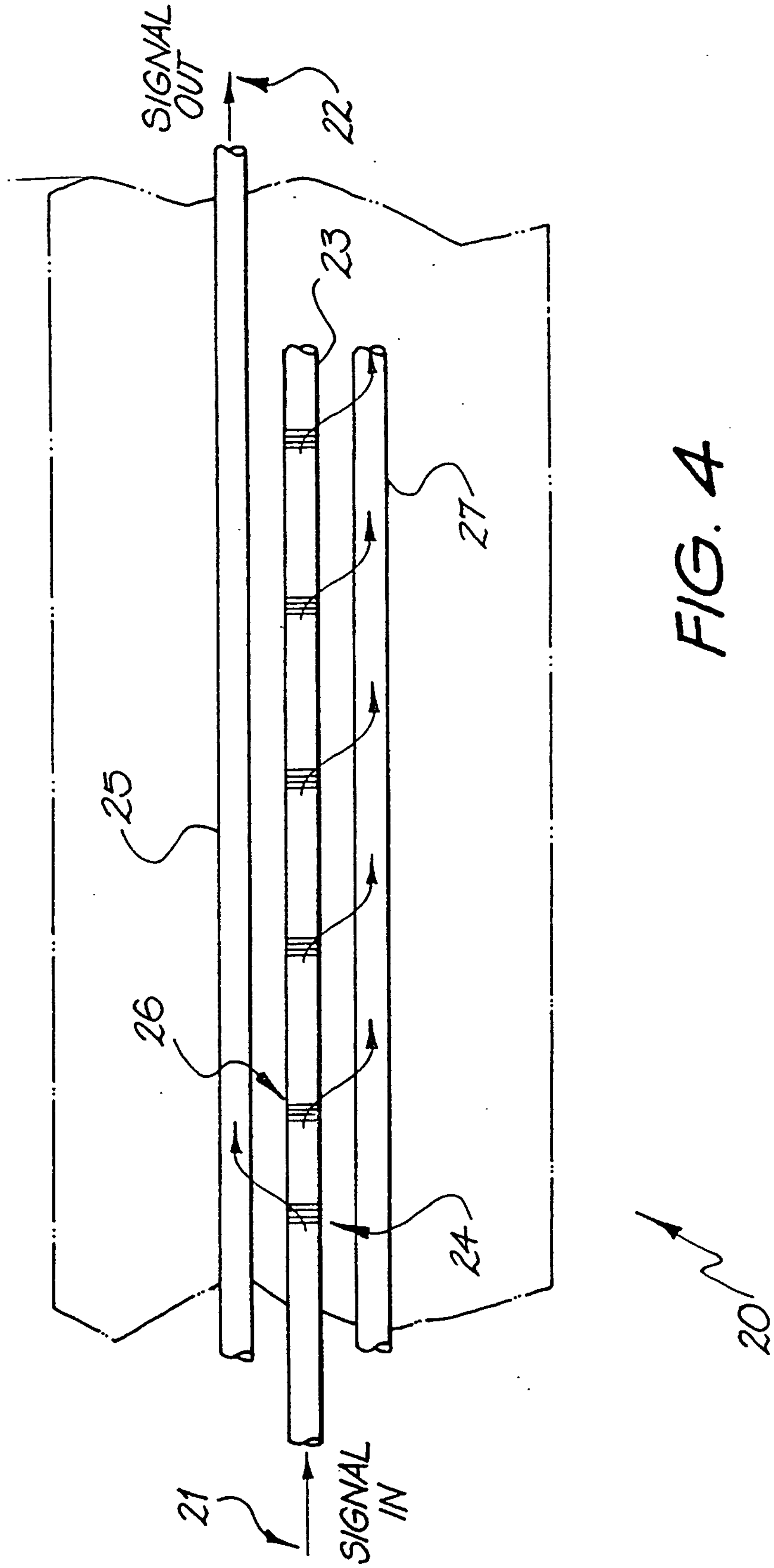

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 99/00129

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: G02B 6/22

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: G02B 6/-, POST 1990

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT and JAPIO: [(AMPLIF: OR GAIN) AND COUPL:] OR NOISE OR FLAT OR CONSTANT OR GRATING

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	US 5430817 A (VENGSARKER) 4 July 1995	
X		1-8,10-14
Y		1-3,5-8,10
	US 5260823 A (PAYNE et al) 9 November 1993	
X		11-14
Y		1-3,5-8,10
	US 5271024 A (HUBER) 14 December 1993	
X		11-14
Y		1-3,5-8,10

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
30 March 1999

Date of mailing of the international search report
15 APR 1999

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 99/00129

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 93/07664 A (BRITISH TELECOMMUNICATIONS) 15 April 1993	11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 99/00129

Box 1 Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims No.: 9
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

The scope of the claim is so broad, no international search strategy could be determined.

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU 99/00129

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	5430817	CA	2141899	EP	675611	JP	7283786
US	5260823	EP	535002	GB	2246234	WO	91/18434
US	5271024	CA	2101364	EP	582860	JP	6177467
		MX	9304491				
WO	93/07664	AU	26479/92	EP	606331	HK	1129/97
		GB	9102925				

END OF ANNEX